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Human velocity discrimination depends on the precise detection of minute time variations (under 1 msec). A physiological summation process called "sequential recruitment" is responsible for this remarkable temporal sensitivity. Precise velocity discrimination is possible with very brief target durations (less than 100 msec). The oculomotor system uses this sensory signal to initiate smooth pursuit eye movements.

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Human Velocity Discrimination

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I. The Mechanism of Human Velocity Discrimination: Sequential Recruitment and Assimilation

The motion of a target does not have to be continuous to guarantee fine velocity discrimination. Stroboscopic motion, commonly called apparent motion, will work equally well, provided that the spacing between the targets is not too coarse (< 10 min of arc). A target hopping across the screeen at 9 min of arc every 10 msec looks very different from a target moving smoothly across the screen at 15 deg/sec, but the velocity discrimination for these two targets is the same. Figure 1 shows velocity discrimination for continuous and apparent motion as a function of target duration. The development of the velocity signal follows the same time course for the two types of motion. The velocity threshold reaches its asymptotic value of about 5% (a factor of 1.05) in 60 - 80 msec for continuous motion, or equivalently in 7-9 target presentations for the apparent motion stimulus.

Apparent motion has the virtue that the development of the temporal signal essential to velocity judgments can be examined independently of the spatial contribution to velocity. The positions of the target lines making up the apparent motion stimulus can remain the same from trial to trial with target velocity altered by minute changes in the time between each target presentation.

For the apparent motion target made of an 8-line sequence, the detectable incremental change in each of the 10 msec temporal intervals separating the lines was about 0.5 msec. Control experiments ruled out the possibility that the observers had judged velocity on the basis of variations in overall target duration. In principle, a single pair of lines presented asynchronously could supply the necessary timing information, but our experiments demonstrated that a two-line sequence is insufficient. The incremental threshold for a 10 msec asynchrony defined by two lines is roughly 3 msec, a value 6 times the detectable increment for a 8-line sequence.

What is responsible for the improvement in the temporal increment threshold as the number of lines in the sequence increases? One explanation is the phenomenon known as probability summation. No matter how small the incremental change in the asynchrony of any one interval, there is some chance that this increment will be detected. The presentation of many intervals in a sequence increases the probability of a correct detection in at least one of the samples. The largest improvement in threshold should occur as the number of lines increases from two to three. Figure 2 shows the temporal increment thresholds for a single 10 msec asynchrony, a single 20 msec asynchrony and for the three-line sequence. Note that the three-line sequence provides three chances for a correct detection (two 10 msec intervals and one 20 msec interval). The last column of Figure 2 shows the predicted thresholds based on probability summation if the integration model of signal detection theory is used as the basis of the calculations. The predictions of this probability summation model match our results, but the conclusion that probability summation can explain the enhanced temporal sensitivity may be unwarranted.

For one thing, the probability summation calculations assume that each of the components of the three-line stimulus are independent events. Is it reasonable to expect that targets separated by less than 20 minutes of arc and 20 msec of time are actually independent events for the human visual system? The independence assumption is crucial to any model of probability summation, and there is a simple test of this assumption. For probability summation, it should not matter if the lines are presented in the regular sequence of a motion stimulus. Any stimulus arrangement in space or time which provides three stimulus events similar to the components of the three-line sequence should produce the same low threshold.

Two stimulus variants were used to test this assumption. Three asynchronous intervals were presented in the vertical array diagrammed in Figure 3 (labeled "simultaneous"). The thresholds for this arrangement were much higher than for the three-line sequence. In fact, the thresholds for this vertical array showed no improvement over the thresholds observed for a single 20 msec interval. In the next experiment diagrammed in Figure 4, observers were asked to wait until they had seen three successive samples before judging incremental changes in a 10 msec asynchrony. A 170 msec period intervened between each presented sample. Again there was no marked improvement in the thresholds if compared to the threshold obtained with a single 10 msec sample, unlike the enhanced detectability observed with the three-line sequence.

The observers were unable to use the information available in the additional target presentations unless the targets were presented in a regular motion sequence. Because there was no improvement in asynchrony thresholds for the stimulus configurations diagrammed on the right of Figures 3 and 4, it is unlikely that these stimuli are treated as independent events by the visual system. Therefore, the marked improvement in discrimination produced by the three-line sequence must arise from physiological summation of the timing signals via a special physiological network responsive to motion. We call this physiological summation process -- "Sequential Recruitment".

This laboratory is now examining the experimental consequences of sequential recruitment in a collaboration with Dr. Donald I.A. MacLeod from the University of California at San Diego. For example, if the signals from a sequence are pooled, then, while some threshold processes are enhanced, others are degraded. In one experiment, observers had great difficulty discriminating a three-line sequence in which the first temporal interval was 30 msec and second interval was 10 msec from three-line sequence in which the first interval was 10 msec and the second 30 msec. Basically a 30-10 combination and a 10-30 combination appeared as a single equivalent velocity. This result argues for an assimilation of timing signals, an averaging process which enhances the velocity discrimination. Other results indicate that sequential recruitment can only occur along a single direction. Orthogonal signals are not pooled. Specifically, if the three-line sequence consists of a pair of vertical lines presented asynchronously one above the other followed a third vertical line presented parallel to the first two, no sequential recruitment is found.

II. The Precision of Smooth Pursuit Eye Movements

Target velocity is thought to constitute a primary signal for the smooth pursuit system. In the laboratory of Dr. Eileen Kowler at Rutgers University, the precision of smooth pursuit was compared to the precision of psychophysical judgements of velocity. Since the precise psychophysical discrimination of velocity can be accomplished with target durations of less than 100 msec (Figure 1), it is possible that the oculomotor system could use the sensory signal as the basis for the initial pursuit velocity. In the sensory judgments, the subject is shown one of five velocities chosen from a narrow range, and is forced to indicate whether the presented sample is faster or slower than the mean of the range. No standard velocity is ever presented; subjects judge each sample against an implicit standard defined by feedback and sequence of trials. The psychophysical velocity threshold is defined as the velocity increment required to change the subject's response from 50% to 75%, equivalent to a d' of .67.

The precision of eye velocity (the oculomotor output) was judged in an analogous way. Typically the gain of the pursuit system is less than 1.0, so the eyes always move at a velocity less than the target velocity. Nevertheless, given the same velocity range used for the psychophysical measurements, the eyes should move faster for velocities above the mean of the set, and slower for velocities that are less than the mean. The oculomotor output can be used like a psychophysical response. If the target velocity is greater than the mean of the set of five test velocities, and the eyes move faster than the mean oculomotor value, the response is judged as "correct", because the oculomotor system is detecting an incremental change in velocity. Direct comparison of the slope of the psychometric function generated by the oculomotor velocities to the slope of the psychophysical psychometric function was used to test the relative sensitivity of the sensory and motor systems.

An SRI eye tracker was used to measure pursuit velocities to targets moving 0.5 deg/sec, 3.3 deg/sec, and 5 deg/sec. The two faster velocities were tracked more precisely than the slow velocity. On the basis of the differential response shown by the smooth pursuit velocities, Kowler and McKee concluded that the oculomotor system was sensitive to an 8 - 10 percent change in velocity at 3.3 deg/sec or 5 deg/sec but could only detect a 25 - 30 percent change in a velocity of 0.5 deg/sec. A parallel pattern of results is found in most psychophysical studies of sensory velocity discrimination. In the absence of other cues, observers cannot detect small changes in velocities below 1 deg/sec. The oculomotor system requires 400-500 msec to achieve this degree of precision, so it is possible that retinal feedback is controlling the fine tuning of this response. However, the initial velocity of pursuit, measured 150-300 milliseconds after the target begins moving, showed indications of a differential response to the target velocity which must be based on the sensory input.

In the fall, Dr. Kowler and I will continue our colloboration on a different aspect of the inter-relation between the oculomotor and sensory systems. We plan to measure the sensory discrimination of velocity when the eyes are tracking another target. If the eyes were tracking a target at 5 deg/sec and a second target, moving at a different velocity, were presented briefly (< 150 msec), how well could the observer respond to incremental changes in the velocity of the second target? In this case we plan to judge the observers' psychophysical responses on the basis of the actual retinal velocity by taking account of the eye velocity at the time of the presentation of the second target.

III. The Binocular Correspondence Problem of Human Stereopsis

In the past six months, this laboratory has also been studying the correspondence problem in stereopsis, a project which was not part of the original research proposal. Binocular correspondence is the study of how the two monocular images are correctly fused in normal binocular vision. Dr. Graeme Mitchison, consultant to this project, created a novel stimulus configuration, which can be used to discover the "matching" rules employed by the visual system in fusing the two half-images. Julesz' random dot stereograms have been used for this purpose, of course, but this stimulus has the virtue that it can be implemented with a microprocessor-based system.

The stimulus for this study was a regular grid composed of many columns of bright points. Any repetitive pattern is an ambiguous stereogram which can be potentially fused in several different depth planes (wallpaper effect). If a steep disparity gradient is added to the edges of this simple grid, the whole grid appears to move forward in depth, without the intervention of changes in convergence. The depth of the central region of the grid was measured by placing a test point below the grid and asking the observer to signal whether the briefly-presented grid (160 msec) was in front or behind the position of the test point. A disparity gradient is defined as the ratio of the difference in disparity between adjacent points to their lateral separation. Burt and Julesz reported that two points appeared diplopic if the disparity gradient separating the points was too steep. In this experiment, the disparity gradient at the edges forces an alternative matching solution across the entire grid.

In the next six months, several experiments on this matching phenomenon are planned, using this simple pattern as a probe of binocular correspondence. The binocular correspondence problem has been treated extensively by the Artificial Intelligence community, but our initial tests indicate that Marr-Poggio models of stereopsis will not explain the our results. The spatial and temporal properties of grid-gradient effects will be explored.

IV. Publications

McKee, S.P. and Nakayama, K. The detection of motion in the peripheral visual field. _Vision Res._, 24, 25-32, (1984).

McKee, S.P., Silverman, G.S., and Nakayama, K. Precise discrimination of velocity despite random variations in temporal frequency. Submitted to _Nature_

McKee, S.P. and Welch, L. Sequential recruitment in velocity discrimination. To be submitted to _J. Opt. Soc. Am._

McKee, S.P., Silverman, Gerald, and Nakayama, K. Velocity discrimination is not affected by random variations in temporal frequency. _Invest. Ophthal. and Vis. Science_ suppl., 25, (1984)

Kowler, Eileen and McKee, S.P. The precision of smooth pursuit. _Invest. Ophthal. and Vis. Science_, suppl., 25, (1984)

Mitchison, G. J. and McKee, S.P. Fine control of depth planes in a wallpaper stereogram. To be submitted to _Nature_.
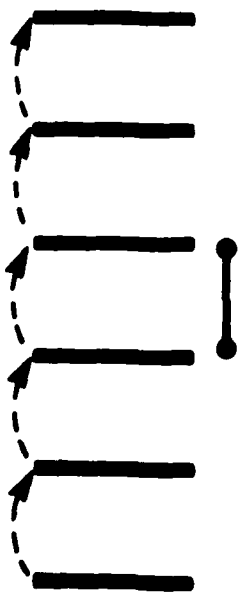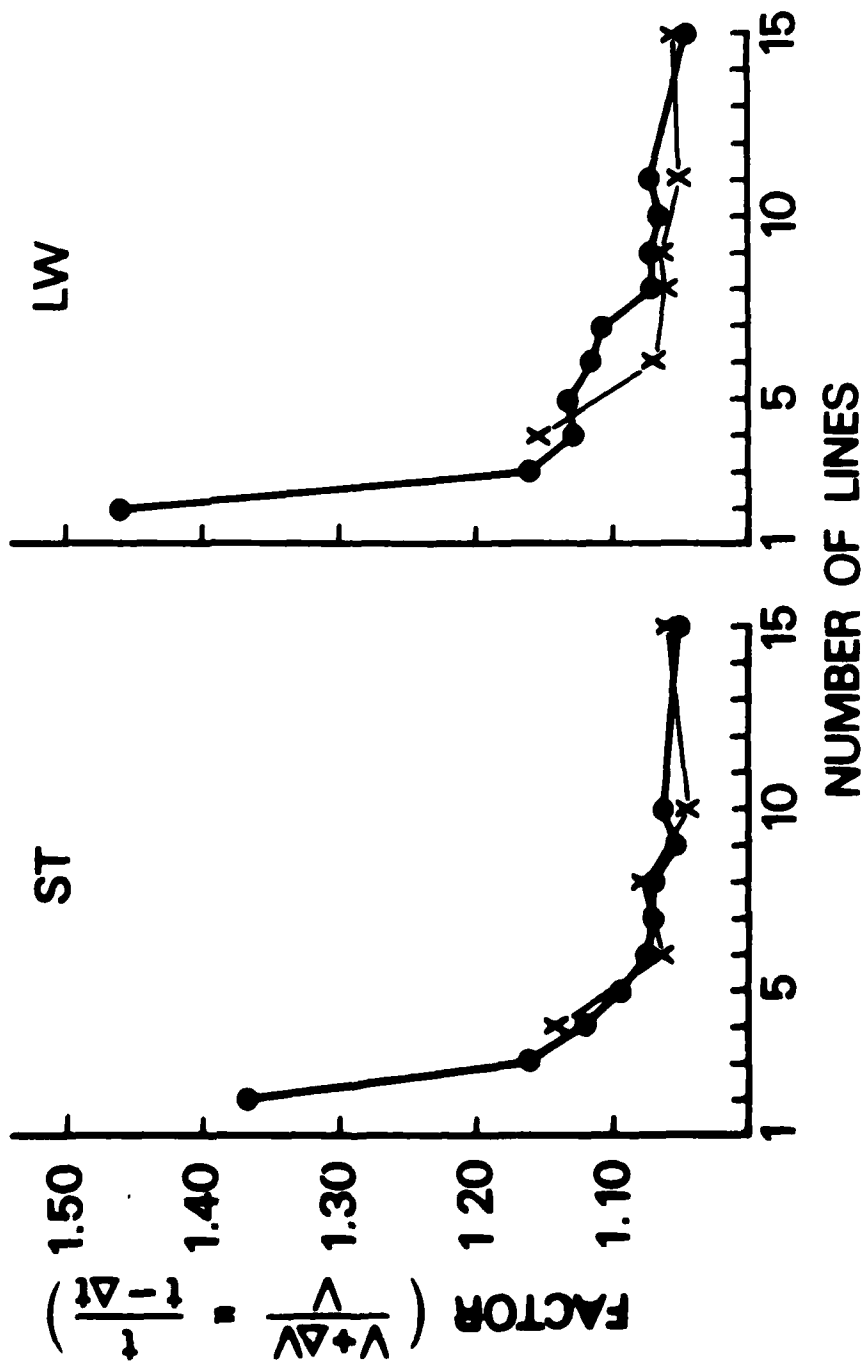
Figure 1

PROBABILITY SUMMATION
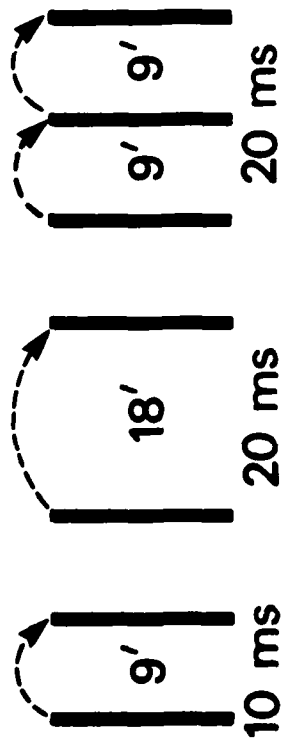
	10 ms	20 ms	20 ms		PROBABILITY SUMMATION
	9'	18'	9' 9'		
LW	3.2 ms	5.9 ms	2.6 ms		3.4 ms
SM	3.5	6.8	3.4		4.0
DT	2.7	5.0	3.3		3.2
ST	2.7	7.3	2.8		3.3
Ave. %	30%	31%	15%		17%
Factor	1.43	1.45	1.18		1.21

Figure 2

SEQUENTIAL   SIMULTANEOUS

18′

20 ms

9′ | 9′

20 ms

9′

10 ms

9′
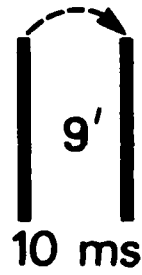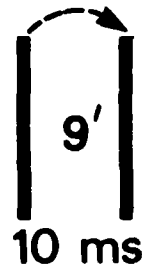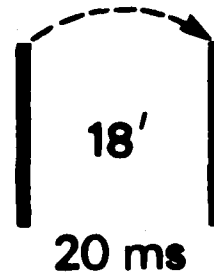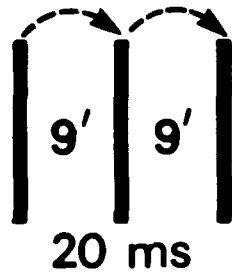
10 ms

LW	2.6 ms	6.5 ms
SM	3.4	7.2
DT	3.3	5.2
ST	2.8	5.4

Ave. %   15%   30%

Factor   1.18   1.43

Figure 3

SEQUENTIAL RECRUITMENT

THREE SUCCESSIVE OBSERVATIONS OF 10 ms STIMULUS

LW	1.3 ms	2.6 ms
SM	1.7	3.9
DT	1.7	2.5
ST	1.4	3.5
Ave. %	15%	31%
Factor	1.18	1.45

Figure 4

END